The dry channels at Ballyfoyle, Co. Kilkenny: a relict landscape of subglacial water

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(Received 7 June 2012; final version received 4 March 2013)

This paper examines the geomorphology of a suite of deep channels around the village of Ballyfoyle on the Castlecomer Plateau, Co. Kilkenny, and suggests a mechanism for their formation. The channels were mapped using a 10-m digital terrain model and ground truthed in the field. The channel locations were superimposed on a bedrock map of the area. Sediments within two passages of the nearby Dunmore Cave were also examined. While the cave sediments represent flow within a karstic system from a stream with its origin outside of the cave system itself, and possibly indicate subglacial flow, the adjacent channels are all eroded into bedrock that would have acted as a poor aquifer beneath the glacier. The channels are therefore interpreted as subglacial meltwater channels. The paper suggests that the aquifer characteristics were important in determining the method of subglacial hydrology present during glaciation in this area.

Keywords: meltwater channels; glaciation; south-east Ireland; karstic systems; subglacial hydrology

Introduction

The growth and decay of the last, Late Midlandian, ice sheet in Ireland produced a range of glacial erosional and depositional landforms across the country. While much previous work has focused, in particular, on glacial depositional forms such as drumlins, eskers and rogen moraines (e.g. McCabe and Dardis 1989, McCabe 1991, Warren and Ashley 1994, Knight and McCabe 1997, Meehan et al. 1997, Delaney 2002, Knight 2010, Pellicer and Gibson 2011), there have been relatively few recent investigations of glacial meltwater channels.

The occurrence of deep, dry channels on the Castlecomer Plateau in County Kilkenny has long been known. Charlesworth (1928) described a suite of these on the Castlecomer Plateau as ice-marginal channels and mapped them for his South of Ireland End Moraine paper (Charlesworth 1928). Charlesworth mapped 16 channels in the area, although subsequent work mapped 18 channels (Hegarty 2003). In his 1928 article, Charlesworth talks about the channels, which he interpreted as proglacial, as having been formed in association with what he terms a moraine, on the western side of the Castlecomer Plateau. He also mentions that a number of similar channels occur on the south-eastern slopes of the Plateau (p. 327). In 2008, the area was added to the list of sites of geological heritage of Kilkenny, with a suggestion that it be included as a proposed National Heritage Area. The heritage

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audit for the county (Clarke et al. 2007) included the Ballyfoyle channels as one of its heritage sites, under the category of Quaternary geomorphology. While it interpreted the channels as Nye channels (subglacial meltwater channels), it provided no rationale for this interpretation.

This paper will examine the geomorphology of these channels and the surrounding landscape, including an aspect of nearby Dunmore Cave, in the light of knowledge about subglacial meltwater flows. It will look at how channels might have been developed in this area. The paper will begin with a brief summary review of the current knowledge of subglacial flows and their geomorphology.

Subglacial meltwater channels

During the last glaciation, the ice sheet that covered Ireland was wet-based over much of its geometry (Greenwood and Clark 2009). At the base of the ice sheet, meltwater is released by pressure melting of glacier ice as it comes up against bedrock obstructions, or is supplied to the bed from the other areas within the glacier. It can also be produced from the heating of the base of the ice by a geothermal heat source. If the pressure within the water exceeds the pressure that is exerted on it by the overlying ice (cryostatic pressure or ice-overburden pressure), then the effective pressure at the base of the glacier becomes zero and the ice sheet is destabilised. Therefore, when water pressure approaches the value of ice overburden pressure, or when the effective pressure (cryostatic pressure less water pressure) approaches zero, drainage routes are created beneath the glacier to carry the excess water to the glacier front and so dissipate the excess pressure (Hindmarsh 1997) and stabilise the ice sheet.

Where thick, high-transmissivity beds occur beneath glaciers, a large quantity, if not all, of the glacial meltwater can be transported to the area in front of the ice sheet via this medium. However, in an area with low bed transmissivity, meltwater must be transported to the glacier front via subglacial meltwater channels or as a sheet at the ice/substrate interface (Piotrowski 1997a). This variation should lead to different geomorphological terrains in the areas involved. If a high transmissivity subglacial bed (an aquifer) was used as a meltwater conduit, no sign of subglacial meltwater conduits should be seen on the land surface following deglaciation. However, where drainage is via meltwater conduits at the ice/substrate interface, these channels should be seen on the post-glacial landscape, as will be discussed below.

Weertman (1972) suggested that, if the bed of the glacier were impermeable to water, basal meltwater would discharge via a thin film. Walder (1982) went on to develop this theory and argued that meltwater would only flow in what became known as ‘Weertman films’ if the basal pressure were equal to cryostatic pressure. Therefore, at high cryostatic pressure areas, no water film would exist. As the cryostatic pressure gradient is largely a product of the ice sheet thickness (the thicker the ice, the greater the cryostatic pressure), the effect of this pressure is to direct the flow of water perpendicular to the surface slope of the glacier. This results in the surface slope of the glacier being more effective at directing water flow than the surface slope of the substrate, the local topography, itself. Thus, subglacial meltwater channels can run across ridges or parallel to pre-existing contours.

Walder (1982) suggested that, given the nature of sheet flow, a thicker water sheet will occur in areas of an unevenly bedded substrate. In these areas, different hydraulic pressures will evolve. Water will flow preferentially into these areas of lower pressure (as water flows from areas of high pressure to areas of lower pressure). Increased water flow in these subglacial areas will increase the friction of water on the overlying glacier ice. This will lead to an increase in the size of the incipient channel, until a sizeable channel eroded up into the ice, or a Röthlisberger channel (R-channel; Röthlisberger 1972), is obtained. Paterson (1994) points out that R-channels can collect basal meltwater from a wide area from under stagnant ice, whereas under a moving ice sheet only a limited region can be drained. It is within this type of an environment that eskers are deposited (Shreve 1985, Clark and Walder 1994, Warren and Ashley 1994, Piotrowski 1997a).

Nye channels (Nye 1973, 1976) are described as subglacial channels eroded by meltwater into bedrock. Like R-channels described above, they occur when the subglacial water pressure is high. These conduits generally parallel ice flow direction (they are perpendicular to the surface slope of the ice sheet) and are of moderate to large size (Drewry 1986), when they are sometimes referred to as tunnel channels (see Beaney 2002). Smaller channels have been also documented, in Alpine areas (Bates et al. 2003) and also in sandstones in England (Glasser and Hambrey 1998), where the Nye channels are 1 m in depth. In all cases, the channels are eroded into bedrock, have abrupt incisions and terminations and have steep sides with flat bottoms. The larger channels often have an undulating ('up and down') long profile (Menzies and Shilts 1996).

Nye channels occur when the bedrock is more easily erodible than the ice, that is, when the bedrock is weak, or when the ice sheet or glacier flows over a prior conduit system (Menzies and Shilts 1996). The erosion of these channels into subglacial bedrock suggests long-term channel stability (Hubbard and Nienow 1997). Nye channels are therefore a more stable drainage system and a more efficient system, than the R-channels (Piotrowski 1997a) as R-channels are incised into a medium (ice) capable of closing, while Nye channels, once incised, are permanent if discharge within them inhibits sedimentation. Once incised into the bedrock, subglacial channels will lower the cryostatic pressure at the base of the ice, and therefore will attract further meltwater, increasing discharge, which also leads to the channel's permanency.

Later work has suggested that this view of dividing subglacial channels into R-channels and Nye channels was dependent on the ice sheet flowing over a rigid bed (Boulton and Hindmarsh 1987, Clark and Walder 1994, Walder and Fowler 1994). In areas of deformable sediment, where clay content is high and therefore creep within the sediments is possible, they argued that the different behaviour of the substrate should strongly affect the shape of subglacial drainage conduits. In these areas, what Walder and Fowler (1994) denominate 'canals' exist. These are wide streams incised into the soft sediment and capped by a flat roof of ice. Walder and Fowler predict the discharge to be directly proportional to the water pressure within the canal. Therefore, unlike the R-channels, the canals do not form an arborescent network, but are instead uniformly distributed over the glacier bed, occasionally forming a braided pattern, as high water pressures will force water out of larger conduits into smaller ones (Clark and Walder 1994). These types of conduits are assumed to form where the ice sheet flows over areas of high-clay-content tills and if the ice-surface slope is low. If the ice-surface slope is low, the possibility of focusing meltwater at the glacier bed is eliminated. The focusing of meltwater at the base, as discussed earlier, would produce an R-channel network.

The formation process of large tunnel valleys has been linked both to R-channels and to Nye channels, as well as suggestions of these channels occurring because of catastrophic subglacial floods (Ó Cofaigh 1996). However, the channels seen in Ballyfoyle are generally not of the magnitude of those described in the literature on tunnel valleys, although channels described as Nye channels in the Nore valley (Clarke et al. 2007), to the south of the study area, may be of the magnitude to be considered tunnel valleys.

As mentioned above, these conditions for meltwater channels at the base may not occur when the glacier or ice sheet is flowing over a bed that allows water to flow through it. Flow of subglacial meltwater through a subglacial aquifer during glaciation has been explored for some time (e.g. Boulton et al. 1993, Boulton et al. 1995, Boulton and Caban 1995, Forsberg 1996, Piotrowski 1997b, Fleming and Clark 2000, Carlson et al. 2007, Lemieux et al. 2008). Meltwater from glaciers and ice sheets that overlay impermeable bedrock may have had to rely on tunnels and other forms of subglacial conduit to dissipate the excess water at the base. However, many of the ice sheets of the Quaternary lay over aquifers that had the capacity to carry some water to the ice front (Boulton et al. 1993). If water were carried in the subglacial aquifer, this would dissipate hydrostatic pressures considerably (Boulton et al. 1993). The groundwater catchments which Boulton and his co-workers envisage are far more extensive than the local, interglacial groundwater catchments with which we are familiar nowadays. Indeed, given the added pressure which would be exerted on these aquifers, recharge could be quite deep and water could flow considerable distances, and even uphill.

Boulton et al. (1995) suggest that the aquifers that underlay the core of the European ice sheets had sufficient transmissivity to discharge all subglacial meltwater and therefore to bring water pressures below ice-overburden pressures. They go on to suggest that groundwater flow controls the spacing of other forms of subglacial conduits. This is because the amount of water available at the bed of the glacier is dependent on the transmissivity of the aquifer. If all water is drained via the bedrock, channels or other conduits will obviously not be formed at the base of the glacier as water pressure is below ice-overburden pressure; indeed, water may no longer exist at the base.

However, groundwater flow is often not capable of draining all the water from the base of an ice sheet (Hindmarsh 1998). This is particularly true in the case of Ireland, where the complex geological history has produced an equally complex series of aquifers and aquitards, often not extending for great distances. Therefore, under the Irish Ice Sheet, a further method of meltwater drainage such as those mentioned above may also have operated. This situation of small-scale changes of aquifer characteristics is true of the study area, as is discussed below.

The influence of glaciers on karstic systems has also been studied in both Canada and the Alps. Smart and Ford (1983) suggested that the Columbia Icefield was draining a major portion of its subglacial meltwater through the karstic aquifer of the Castleguard Formations. Karst development is also initiated in subglacial terrain by the overdeepening of a valley by the glacier. This lowers the height of the springline and so steepens the hydraulic gradient (Ford 1996). However, the sealing of karstic systems by fine-grained tills being injected by ice into the conduits can inhibit karstic drainage in an area (Karolyi and Ford 1983). Sharp et al. (1989) describe an area of the Glacier de Tsanfleuron, Switzerland, where the subglacial drainage in the area of carbonate bedrock was via Nye channels that led into well-developed sinkholes, which they suggest indicates that the subglacial drainage system was intimately linked to the subterranean karst system. They also point out that a number of sinkholes have Nye channels leading away from them, suggesting that at times of high discharge the sinkhole would overflow, or that at times the sink would be infilled by ice and so karstic drainage would be inhibited. However, unlike Nye channels and R-channels, the initiation of a subglacial, subterranean meltwater system through a pre-existing karstic network is not dependent on the effective pressure at the base.

Karstic subglacial flow

Sediments within caves have been identified within the study area, and elsewhere within Ireland. The current discussion will focus on clastic sediments within caves, rather than muds or calcite deposits which may be autochthonous.

It has long been known that Dunmore Cave, within the study area, contained passages that had been blocked with sediments (Foot 1870, Hardman 1875, Praeger 1918, Dunnington and Coleman 1950, Drew and Huddart 1980). The most extensive survey of the cave was carried out by Drew and Huddart in 1973 for the Office of Public Works (OPW). Within a phreatic passage called the Rabbit’s Burrow (Figure 6), the authors describe parallel laminated fine sands and silts with some small pebble gravels (Drew and Huddart 1980). The sequence dips towards the south, where it seems to disappear beneath the boulder choke of the Cathedral chamber (Figure 6). Drew and Huddart say that the sediments within this passage have formed differently from those of the rest of the cave, as the gravel lithologies are more varied. They conclude that the sediments have been brought into the cave from a fluvial system originating outside the cave itself. They interpret these sediments as having been brought into the cave during deglaciation, when meltwater would have sunk underground in the Dinin valley to the north and flowed along a zone of weakness in the rocks, to create the Rabbit’s Burrow passage, before exiting in an unknown point to the south of the cave (Drew and Huddart 1980). The top 0.01 m of flowstone on top of the sediments within the Rabbit Burrow was dated using carbon 14 dating by Drew and Huddart (1980). This gave a date of 5665±320 BP. Assuming a constant rate of calcite accumulation, they suggest that the 0.1 m of flowstone within the passage began to form 50,000 years ago. Thus, the sediments within the Rabbit’s Burrow are attributed to early in Oxygen Isotope Stage 3, or late in Oxygen Isotope Stage 4.

On the west coast of Ireland, Simms (2000) describes coarse, quartz-rich sediments within a phreatic passage in a cave in the Burren, Co. Clare. As the lithology of the cave sediments is significantly different from that of the overlying till, Simms argues that they are the result of an older till which was deposited by ice flowing from the northwest, plugging a karstic hollow, possibly during Oxygen Isotope Stage 4. This till was subsequently reworked by streams which flushed the clasts into the cave system before the emplacement of the till above the cave system during Oxygen Isotope Stage 2.

Given what has been outlined about subglacial hydrology, this paper aims to describe the geomorphology of the channels which have been described as Nye channels (Clarke et al. 2007) in Ballyfoyle and provide a possible explanation for their genesis. The paper will also re-examine the sediments in the adjacent Dunmore Cave, which have previously been described by Drew and Huddart (1980), and ask if these sediments can be related to the meltwater channels. Due to the influence of the bedrock permeability and transmissivity on subglacial hydrology, and potentially on the formation of these channels, a description of the bedrock of the study area will be included.

The study area

The channels at Ballyfoyle occur on the southern slopes of the Castlecomer Plateau, an upland area in the southeast of Ireland (Figure 1a). Composed of Upper Carboniferous rocks, the area is best known as one of the major coal mining areas of Ireland (part of the Leinster coalfield). The highest points of the Castlecomer Plateau are on the Upper Carboniferous sandstones at Mountnugent Upper [334 m Malin Ordnance Datum (OD)]. The Castlecomer Plateau has a topographical expression of a basin, due to east–west compression during the Variscan orogeny. The rim reaches heights of over 300 m OD above the limestone lowlands of Carlow and central Kilkenny, while in the centre of the basin the height is an average of 100 m OD in the Dinin Valley.

Bedrock

The rocks of the area are the lowest strata of the Upper Carboniferous sandstones and shales, with a small inlier of limestone occurring to the southwest of the study area (Figure 1b). The Upper Carboniferous strata are of Namurian and Westphalian age. The Namurian rocks generally form the edge of the plateau, where siltstones and sandstones dominate. The coal bearing, cyclical successions of the Westphalian strata occupy the centre of the plateau, which is topographically lower (Tietzsch-Tyler and Sleeman 1994, Sevastopulo 2001). The channels are incised into rocks of the Killeshin formation, a poorly bedded grey silty mudstone formation of Namurian age (Tietzsch-Tyler and Sleeman 1994).

Limestone bedrock

The Middle Carboniferous limestone Clogrennan Formation lies unconformably beneath the grey, argillaceous siltstones and mudstones of the Namurian Killeshin Formation. Due to Variscan folding, which flexed the strata, and subsequent denudation, the Clogrennan Formation is at the surface over a small area and it is within this that Dunmore Cave is found.

As with most Irish rocks, within both formations porosity is secondary, due to fracturing more than to primary inter-granular porosity. In the Clogrennan Formation, the porosity (and therefore transmissivity) is due to the enlargement of pre-existing fractures by the karstification process and not due to inter-porous flow. Permeability is variable and is usually greatest near the surface of the aquifer. In parts of the formation, clay wayboards have restricted permeability and act as

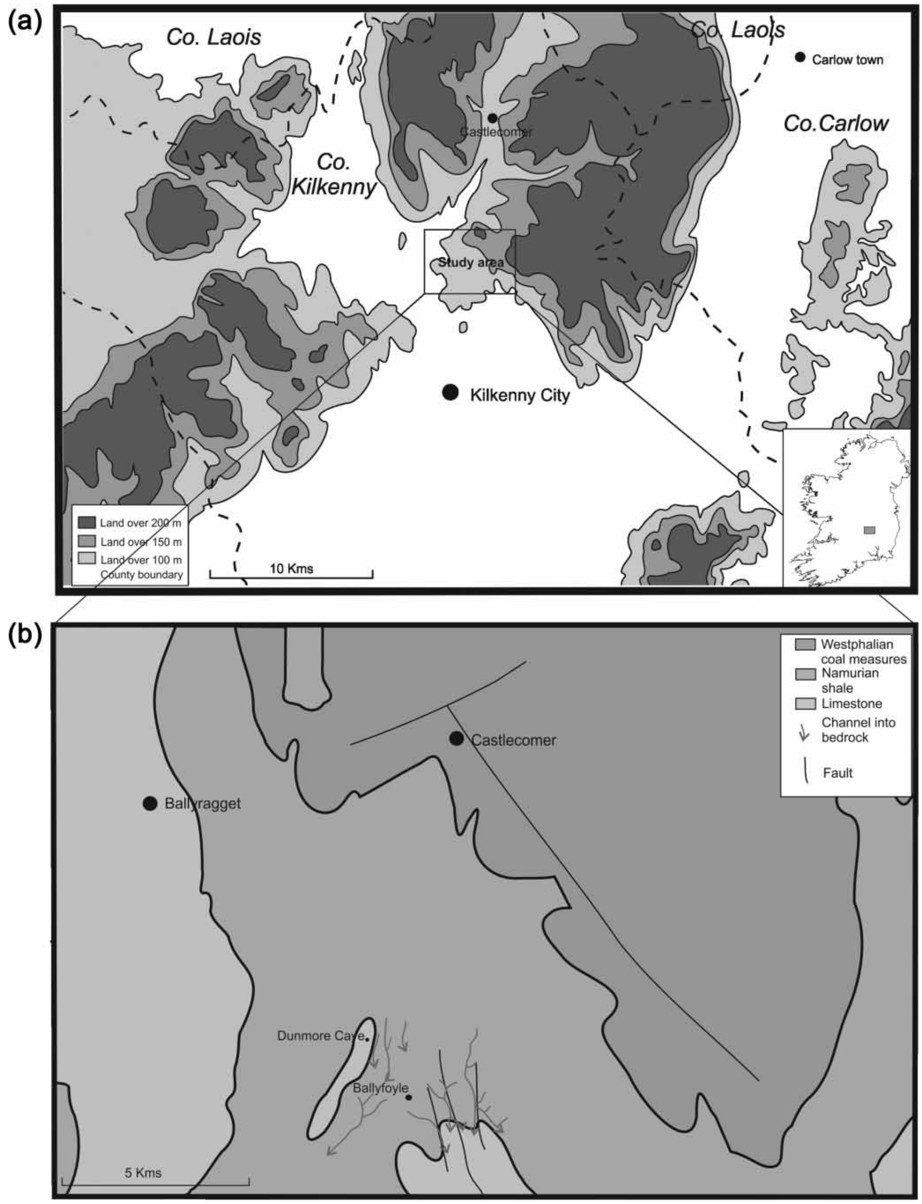

Figure 1. (a) Location of the Castlecomer Plateau and the study area; (b) bedrock geology of the study area, showing the location of the channels and their relationship to the bedrock (after GSI 1:100,000 bedrock map).

barriers (Daly 1994). The formation is confined by the Aghamacart Formation which underlies it and by the overlying shales of the Namurian lithologies. However, only the karstic parts of the Clogrennan Formations are major aquifers. Fissures are usually well developed to depths of 20 m and below that they significantly diminish in size and intensity. Therefore, the formation is not thought to have any major permeability where they lie beneath the Namurian strata (Daly 1994), but only acts as a major aquifer where it is at the surface.

Dunmore Cave

This inlier hosts Dunmore Cave (NGR 250944 165006; see Dunnington and Coleman 1950, Coleman 1965, Drew and Huddart 1980). The cave was opened to the public in the 1960s, after having been taken over by the Commissioners for Public Works in 1944 (Dunnington and Coleman 1950). Dunmore Cave consists of a series of passageways with three chambers. The cave is now fossil, development only occurring through seepages. Modern water level fluctuates within the Crystal Hall chamber, the lowest chamber in the cave system (circa 25 m below the surface). As mentioned above, a number of passages within the cave contain sediments (Rabbit Burrow, Market Cross, Fairies' Floor), some of which, it has been argued, are glaciofluvial in origin (Drew and Huddart 1980, Clarke et al. 2007).

Namurian sandstone bedrock

The Killeshin Formation is composed mainly of grey argillaceous siltstones which are poorly bedded and irregularly fractured. Where shales are present within the formation, they experience onion weathering, usually around a harder nodule of mudstone or ironstone within the siltstones.

Faulting within the Killeshin Formation is consistent with Variscan folding. The main fault of the Castlecomer Plateau, the Coolbaun Fault, runs northeast to southwest, dissecting the plateau in half. Further faults, oriented from northwest to southeast, intersect with the Coolbaun Fault along its length. Further faulting is evident around the Plateau, with most faults following the directional trend of northeast–southwest or southeast–northwest. The Geological Survey of Ireland (GSI) has mapped faults along three of the meltwater channels referred to in this paper (channels 4, 5 and 6 shown in Figure 4). Fracturing within the Killeshin Formation is conchoidal around ironstone nodules and is otherwise irregular (Higgs 1986). It is, therefore, difficult to map the fracturing with any degree of accuracy.

The Killeshin Formation has been classified by the GSI as a poor aquifer which is generally unproductive except for local zones where fracturing may occur (Buckley and Fitzsimons 2001). This is due to the high clay content of the lithology, which when faulted will not have deformed in a brittle manner.

Therefore, within the study area, there are two very different aquifer types; the karstified limestone is a good aquifer that covers a small area, while the Killeshin formation is a poor aquifer. These are the bedrock conditions that would have prevailed beneath the ice sheets of the last glaciation in the area.

Methodology

The channels were first mapped using aerial photography and a 10-m digital terrain model (DTM) of the area, obtained from the Ordnance Survey of Ireland (OSi). The data were obtained by the OSi using digital photogrammetry from the stereo aerial photograph collection flown by Compagnia Generale Ripreseaeree (CGR) in 1995. These photographs were flown at 22,000 feet (approximately 6700 m) above the ground, and produced near vertical photographs at a scale of approximately 1:40,000 (Pinto et al. 1996). The GPS coordinates of the photographs were taken by an onboard system as the photographs were being shot, therefore minimising the amount of control points that were subsequently required by the OSi (Pinto et al. 1996). The DTM that was received from the OSi was visualised within ArcGIS using a triangular irregular network (TIN). This was used to create maps of slope, which enabled the channels to be mapped.

The channels mapped from the DTM were subsequently walked and photographed in the field. The DTM allowed more detailed studies of the geomorphology of the channels to be carried out, such as creating both cross sections and long profiles of channels using the 3D extension of ArcGIS.

Detailed field mapping was carried out on the surface sediments of the area at the scale of 1:25,000, with all available field exposures logged (Figure 2). Locations of rock outcrop were also noted in the field. The GSI nineteenth-century six-inch field sheets were also consulted and all information from them was noted onto modern maps. This information mainly pertained to rock outcrop of the area, although the channels were also noted on the nineteenth-century maps (Figure 3).

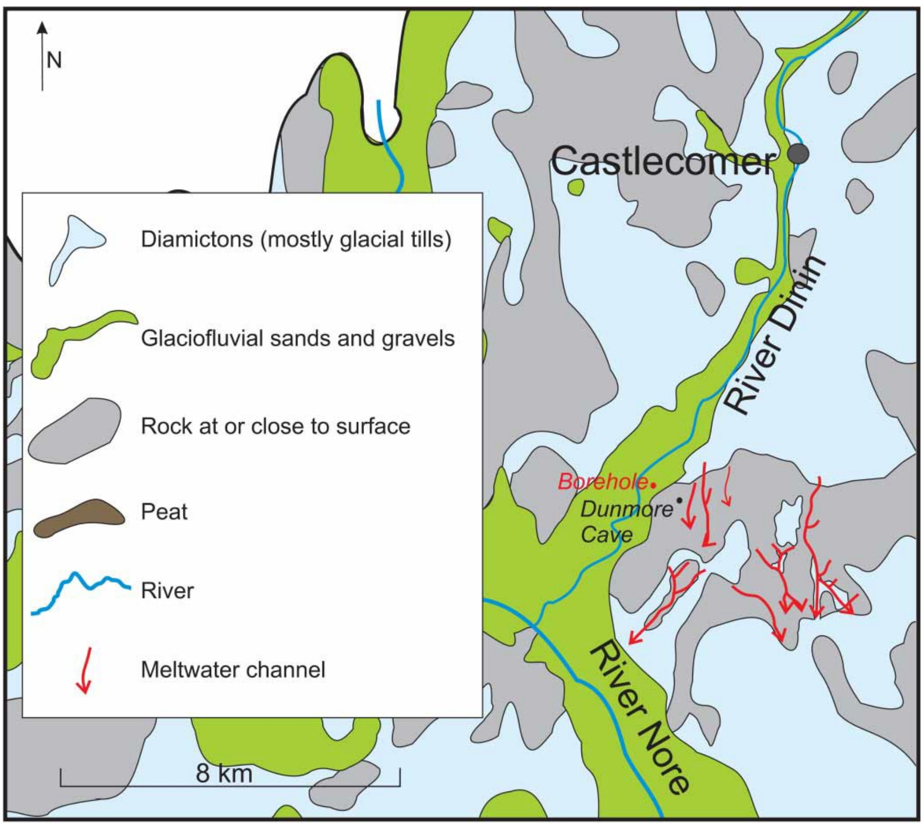

Figure 2. Surface sediments of the study area. Redrawn from Hegarty (2003), EPA subsoil map (Soils and Subsoils data generated by Teagasc with co-operation of the Forest Service, EPA and GSI. Project completed May 2006) and fieldwork.

Figure 3. Nineteenth-century Geological Survey of Ireland field survey map of the study area. Note the deep glens mapped by the surveyor. Dunmore cave is also seen on this map. Source: GSI archive, six-inch sheet 14.2 (digital file S002734.tif). Copyright Geological Survey of Ireland.

Bulk samples of the surface sediments of the area were taken and were wet-sieved for particle size analysis, with petrographic analysis subsequently carried out on the fraction of the sample that fell within the 5–10 mm size range. All of this information was placed within a Geographic Information System (GIS), and overlain on the GSI 1:100 k digital bedrock and aquifer characteristics maps.

Within Dunmore Cave, the sediments in the ‘Rabbit Burrow’ passage of the cave (beyond the publicly accessible cave area) were sketched and photographed. These sediments had a pre-existing trench dug within them to a depth of just over 1 m. As this trench was utilised for sketches, photographs and for sampling, no further damage was done to the cave setting. A small bulk sample was taken from the gravels within this passage for wet sieving and petrographic (stone count) analysis. The dip of the layered sediments within the trench was measured. Photographs and bulk samples were also taken and dips measured within the section of the cave known as ‘The 44’.

Ballyfoyle channels

The suite of seven channels (some with subchannels which coalesce with the main channel) occurs between the 120 and 150 m contours OD (Figure 4). The channels are cut into the Namurian-aged Killeshin formation bedrock. They are steep sided,

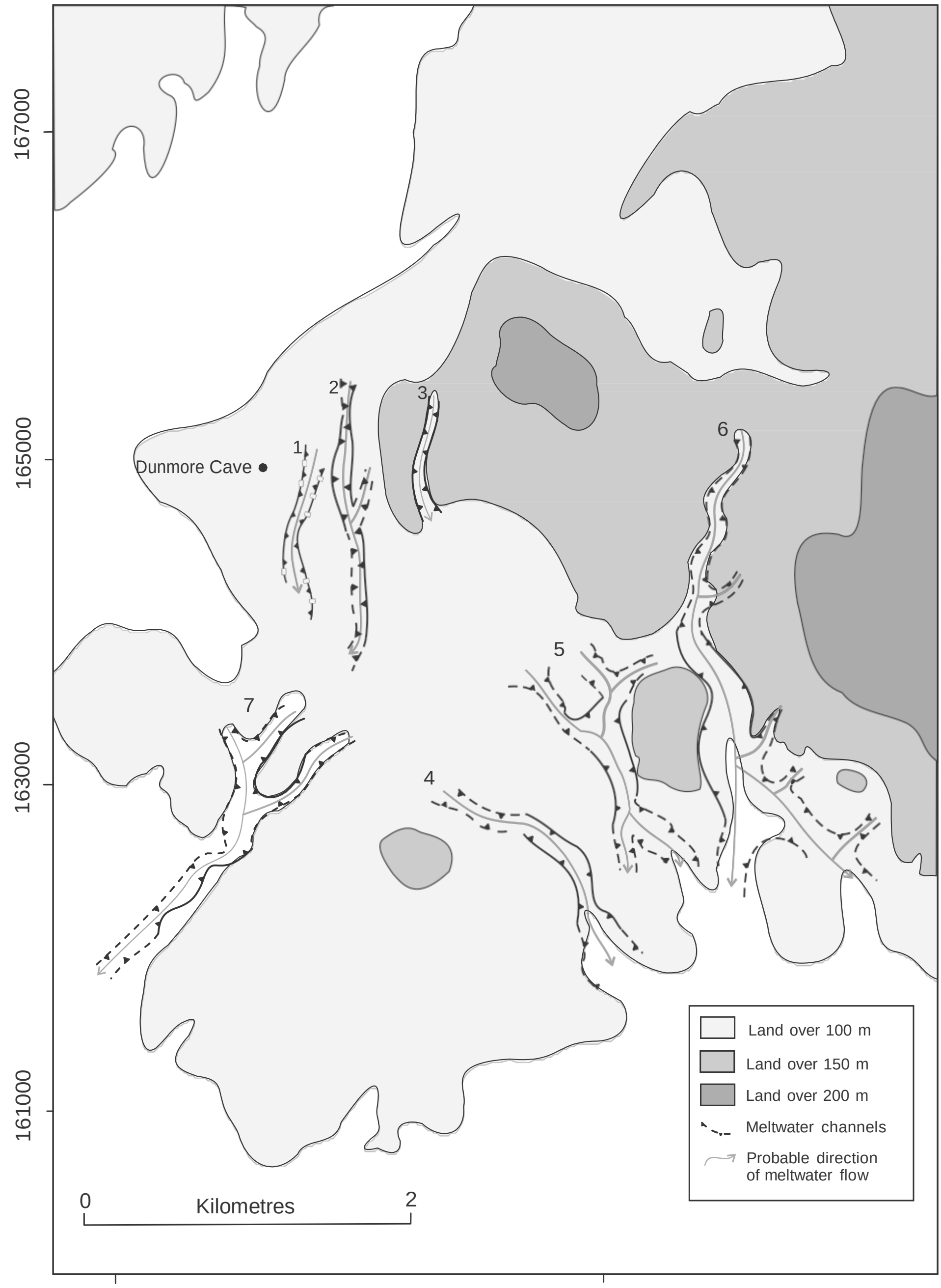

Figure 4. Location of meltwater channels and Dunmore cave, with the numbering system used in this paper.

generally 30 m deep and begin and end suddenly. The longest of the channels (channel 6 in the naming system used in this paper) is just under 3 km long, while the shortest (channel 1) is 0.5 km in length. Some of the channels are trapezoidal, or partially trapezoidal, in form (particularly the larger channels – numbers 4, 5 and 6), while others are more gently 'v' shaped. The cross-sectional geometry of the channels does not evolve greatly from the proximal to the distal end of the channel (Figure 5). Some of the channels are now dry (channels 1 and 4, and the subchannels of 2, 5, 6 and 7), while those that do contain streams are outsized for the small stream that they host.

While the channels are incised into bedrock, some do contain sediments at the base. The depth of these sediments is unknown due to the inaccessibility of the terrain and therefore the difficultly in coring or trenching. The surface sediments of the study area are shown in Figure 2. The largest of the channels are the suite of three (channels 4, 5 and 6) at Ballyfoyle (NGR 252726 163354). These sinuous channels, cut into the bedrock, run west northwest–east southeast and widen to the south. Their length ranges from 1.5 to 2.9 km long and they average 20–30 m in depth, with steep, almost vertical, sides. Channels 5 and 6 have tributaries (subchannels) which join the main channel.

Three other channels occur just to the east of the nearby site of Dunmore Cave. These slightly shallower channels run north–south for lengths of 1–2 km. The depth of these channels averages 20 m, and the sides are steep. As with the previous channels, these are cut into Namurian shale bedrock. Channel 2 has a tributary which runs parallel to the minor road and joins the main channel at NGR 251501 164538. A number of smaller, still shallower channels cut into the bedrock occur around these seven. All these channels generally trend north–south, with minor variations, such as found within the channel at Kilmademoge (channel 7) which trends north northeast–south southwest. Within channel 5, Namurian sandstone and shale-dominated diamicton is found within the flat-bottomed base (Figure 2).

The 10 m DTM was used within ArcGIS to create a longitudinal profile of the bases and cross-sectional profiles of a selection of the channels. One of these, that of the longest of the channels (channel 6), is shown in Figure 5. As can be seen on the cross profiles (Figure 5c), the general slope of the landscape is from east to west (from the right to the left of the graph, generally), with the eastern sides of the channel in general being higher than the western sides. This is typical for all the channels in the area (as can be seen in Figure 4). Into this, the deep channel is cut, within the bedrock. The channel has steep sides and a 'v'-shaped bottom, characteristic of fluvial erosion. At its southern end (Figure 5d) the channel opens out to a flat-bottomed floor. This opening and ending coincide with the shale/ limestone boundary. As can be seen in Figure 5b, the channel has an undulating (up and down) long profile. The major break in slope at 1.2 km from the beginning of channel 6 (Figure 5b) coincides with the point where the subchannel to the east joins the main channel. This would have increased the discharge of the main channel and therefore have led to increased erosion, deepening the meltwater channel.

The majority of the channels in Ballyfoyle have this characteristic shape and do not obey pre-existing topography. Instead, they cut across pre-existing ridges, something that has been observed in subglacial channels in other areas (Booth and Hallet 1993, for example). The channels also begin and end suddenly, have an undulating long profile and some of the channels are trapezoidal for part of their length. These characteristics, along with the undulating long profile, are typical of subglacial meltwater channels (Booth and Hallet 1993, Menzies and Shilts 1996). Owing to these characteristics, the channels have been interpreted here as subglacial meltwater channels. As the channels are carved into bedrock, and given their

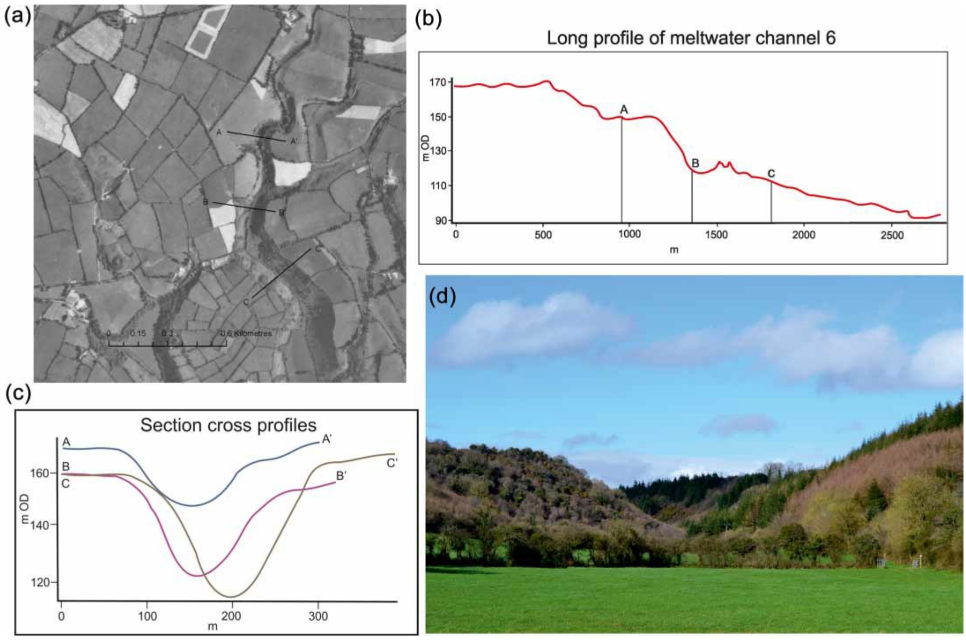

Figure 5. (a) GSI aerial photograph of meltwater channel 6 and locations of cross-sectional profiles seen in (c). (b) Long profile of meltwater channel 6 taken from the OSi 10 m DEM, showing location of cross sections seen in (c). (c) Three cross-sectional profiles of meltwater channel 6, from locations indicated in (a) and (b). (d) Photograph of the termination of meltwater channel 6, at the Namurian shale/limestone boundary, looking north.

medium-scale nature, they are interpreted to be large Nye channels (rather than tunnel valleys, which are larger in scale).

While proglacial meltwater may create channels that are now dry, many dry channels are also sculpted by meltwater flowing beneath the glacier. The suite of channels at Gwaun, in north Pembrokeshire in Wales (John 1970), is similar in geomorphology to the channels at Ballyfoyle, although the dimensions of some of the channels at Gwaun are considerably greater than those at Ballyfoyle. These Welsh channels are also interpreted as being subglacial in origin (John 1970, Sugden and John 1976). In their examination of the glacial features of southwest Wicklow, Farrington and Mitchell (1973) describe the channel at Hollywood (Hollywood Glen), which is of a similar scale to the channels at Ballyfoyle, at 2.2 km in length. It also has an undulating long profile and is cut into bedrock, this time schist. Farrington and Mitchell interpret this channel as being subglacial, the schist being easily eroded by meltwater under high hydrostatic pressure. This channel contains the presence of a small pocket of schist-dominated roughly bedded gravels 10 m above the floor of the channel, which contains small numbers of other lithologies. To the north of county Wicklow, McCabe and ÓCofaigh (1994) described channels which they interpret to by Nye-type channels (see also Hoare 1976). These channels are parallel to ice flow and are incised into rock ridges transverse to ice flow, under high hydrostatic pressure, similar to what has been interpreted for the Ballyfoyle channels.

Possible further evidence for subglacial drainage – Dunmore Cave

As mentioned above, the Rabbit Burrow passage of Dunmore Cave (Figure 6a and 6c), a north–south running roughly rectangular phreatic passage at a depth of approximately 5 m below ground level (Figure 6d), contains sediments which were previously described by Drew and Huddart (1974, 1980). The roof of the passage is a gently dipping bedding plane of the limestone. As with elsewhere in the cave, the true floor of the passage cannot be seen. The passage is to the north of the 'Cathedral' (or Haddon's Hall) area – a zone of roof collapse which created a vaulted roof above a very large bolder choke, and which limits the extent of the modern show-cave. During surveying by Drew and Huddart for the original OPW report (Drew and Huddart 1974), a trench was dug into the sediments to expose the internal structures. For the purpose of this paper, the sediments were re-examined and are described here. These sediments are generally greater than 1 m in thickness (although exact depth cannot be ascertained as digging further into the bed of the trench is not possible). They are made up of bedded, medium to coarse sands, above which there is a layer of gravel. While the beds of sand are in general horizontal, there is some variation to this, with some areas of the trench showing evidence for a braided stream system (with cross-bedding) while other areas, particularly nearer to the boulder choke of the roof collapse, showing faulting, indicating deformation after sedimentation (Figure 6a). The gravels are subangular to subrounded pebble to small cobble-gravel size, and are mostly Namurian sandstone and Westphalian shale, although other lithologies were also present (Figure 6d). There are small amounts of angular limestone, dolomite

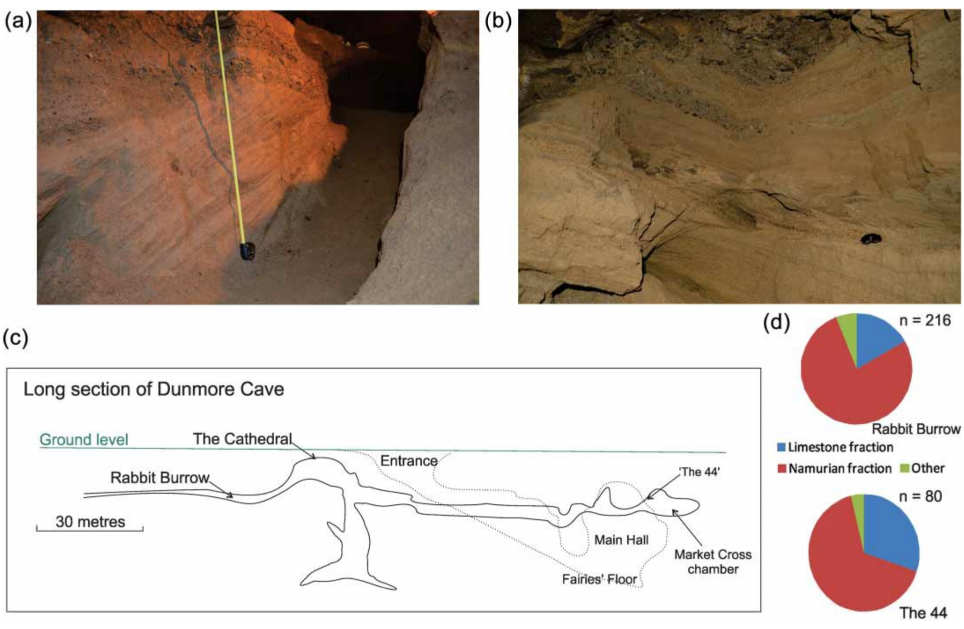

Figure 6. Dunmore Cave. (a) Sand and gravel section within the Rabbit Burrow, looking south. (b) Sand and gravel section within The 44. (c) Sketch of Dunmore Cave, from Dunnington and Coleman (1950), redrawn by kind permission of the Royal Irish Academy. (d) Petrographic analysis of the clasts within the uppermost gravel section of Rabbit Burrow and The 44.

and chert, with some rounded conglomerates also present. On top of the gravels, in hollows on the surface, pockets of silt and clay occur. These small areas of silt and clay are interpreted to represent ponding on the surface of the sand and gravel sediments soon after these were laid down. All of these are covered with a flowstone.

Just to the north of the boulder choke that formed the Cathedral, the sands are overlain by fine silts and clays. Here, the sands, clays and overlying gravels are dipping at approximately 208 to the north. The presence of gravels above the clay layer suggests that, following ponding of water above the sands, there was a further flow of water to the south. The dipping clay layers further suggest that the sequence is deformed, perhaps due to the collapse of the roof to the south and subsequent pile-up of boulders on the floor of the passage. The sands are beneath the boulder choke, therefore indicating that the presence of the stream which deposited them was prior to the roof collapse that caused the Cathedral chamber (and possibly also the roof collapse that caused the entrance to the cave itself).

The presence of a large percentage (64%) of allogenic material from the Rabbit Burrow section of the cave (Figure 6d) suggests that the deposits and hence the water which deposited them, originated outside the cave itself. The input point has not been identified, and it is hypothesised that it is now covered by glacial material, most likely to the north of the cave system. The presence of large, rounded boulders in some parts of the cave, particularly in the Fairies' Floor (the passage between the Side Hall and the Main Hall) and the Town Hall, would suggest that a large river once flowed through the cave (after Drew and Huddart 1980).

While sediments are found elsewhere within the cave, sediments as rich in material carried in from outside the cave are only found within one other known area. In the Town Hall chamber of the cave, squeezing in between boulders in another area of roof collapse, one enters a small chamber known locally as 'The 44'. Here, laminated sands topped by a bed of gravels are found (Figure 6b). This chamber is at the same level as the Rabbit Burrow passage. Here, 0.4 m of steeply dipping laminated coarse sands and fine gravels are overlain by 0.1 m of pebble to cobble-sized gravelly diamicton. Faulting is evident within the sands. On petrographic analysis, the make-up of the gravels is very similar to the gravels found within the Rabbit Burrow area (Figure 6d), although more limestone clasts are seen, with many of these being very weathered. Evidence of faulting adds further to the theory that the seen dips are not primary, but are caused by faulting of the sediments, perhaps by the roof collapses that are above both the sediments within 'The 44' and the Rabbit Burrow passage. The possible links between these sediments and the meltwater channels will be examined further below.

Discussion

Ballyfoyle channels

Given the description of the channels at Ballyfoyle, it is suggested here that these channels are subglacial meltwater channels, or Nye channels. Their undulating long profile and their trapezoid shape are particularly reminiscent of this type of subglacial meltwater channel (Menzies and Shilts 1996).

If the channels at Ballyfoyle are Nye channels, or subglacial meltwater channels, then it is important to relate these to the bedrock, and in particular the transmissivity characteristics, into which these channels were incised. In this way it will be seen if the location of these channels relates to the substrate characteristics and, in particular, to the way subglacial meltwater would interact with the substrate.

All of the channels around Ballyfoyle are incised into the Namurian-aged Killeshin Formation. This formation has been classified as a poor aquifer that is moderately productive in very local zones, mostly around faults, by the GSI (Buckley and Fitzsimons 2001). This is due mainly to the high clay content of the sediments, which will have reduced fracture density as it will not have behaved in a brittle manner during folding. This meant that fractures within the formation are irregular, as described above. Fractures are accentuated around the faults of the formation. The formation is traversed by a series of major faults, only three of which are mapped within the study area (Figure 1b). Indeed, as noted above, channels 4, 5 and 6 appear to coincide with these faults mapped by the GSI within the Killeshin Formation. It is likely that the meltwater would have exploited these weaknesses in the rock. As the formation is a flaggy siltstone formation (Figure 7), it is friable and would have been easily eroded by glacial meltwater.

A corollary of this classification of the aquifer as poor is that permeability within the aquifer is also poor, as the aquifer classification is derived from permeability and transmissivity data. Thus, during the last glaciation over this area, meltwater present at the base of a glacier would have been unable to flow into the underlying bedrock, given a substrate of this nature. A build-up of water beneath the glacier would have caused meltwater pressures to rise. If this had occurred beneath the ice on the Castlecomer Plateau, meltwater conduits would have formed. As the bedrock in this area is soft and friable, if conduits formed they would be incised into this, as opposed

Figure 7. Photograph of meltwater channel 2, showing the Namurian shale bedrock at the left of the photograph, looking south.

to up into the ice. This suggests basal ice and debris with a shear strength greater than that of the bedrock, perhaps due to a high overburden pressure. Thus, Nye-type channels would be formed. Nye channels are formed when subglacial hydrostatic pressure is high and occur when the bedrock characteristics are such that, under high pressures, bedrock is more easily eroded than the ice (Nye 1973, 1976).

It should also be noted that the heads of these meltwater forms on the Castlecomer Plateau coincide, for the most part, with topographic barriers. From Figure 4, it can be seen that channel heads are incised into hills running perpendicular to inferred ice flow directions in the region during glacial maximum (interpreted as being north–south, see Hegarty 2004, Ó Cofaigh et al. 2012). This suggests that channel initiation may not have been entirely dependent on poor transmissivity of the bedrock substrate for initiation. Booth and Hallet (1993) describe a similar situation occurring in Washington State and demonstrate that subglacial meltwater channels are eroded into bedrock at topographic boundaries due to changes in equipotential contours of hydrostatic pressure at these points. McCabe and Ó Cofaigh (1994) further identify the importance of transverse ridges on the formation of Nye channels, through influencing the hydrostatic pressure. While not confirming the hypothesis in the case of the Ballyfoyle channels, if this were the case it would again point to the importance of the substrate on glaciological parameters such as hydrostatic pressure.

Once these channels are eroded into the bedrock, they become a permanent feature of the subglacial conduit system, unless they become infilled with sediment (Hubbard and Nienow 1997). However, as the channels in the Castlecomer Plateau are not infilled, it is interpreted that the meltwater flows through them were sufficiently powerful to prevent infilling with sediments.

The termination of the channels around Ballyfoyle coincides with the boundary between the poor aquifers of the Killeshin Formation and the Lower Limestone shale Formation and the karstified limestone formations to the south (Figure 1b). The coincidence of the termination points of these channels with the change in aquifer classification adds significantly to the evidence that these channels developed on areas of low-permeability bedrock which is friable enough to be more easily eroded than the overlying ice and not on areas of karstic bedrock.

The channels found at Ballyfoyle appear similar morphologically (although smaller) to those described by Beaney (2002) from southern Alberta, Canada, namely a trapezoidal form, steep slopes, flat bottoms and a lack of glaciofluvial material. Beaney suggests an origin by catastrophic subglacial meltwater floods for the Alberta channels with formation occurring just before the onset of deglaciation. However, in the case of the Ballyfoyle channels, and more widely in County Kilkenny, there is no evidence to date for such large-scale floods as jökulhlaups or glacial lake bursts. The channels are also much smaller in scale than those mentioned by Beaney (2002) in her article.

For these channels to have developed on the Castlecomer Plateau, an area that, due to its height, must have been covered by ice during Last Glacial Maximum and not in the retreating phase of glaciation, the features must have been incised some time before 19,000 years BP, as the Castlecomer Plateau emerged from the ice shortly after the furthest southerly extent of the British Irish Ice Sheet, sometime after 23,000 years BP (Clark et al. 2012). The lack of glaciofluvial sediments in the area of the channels would also indicate this as, if the channels were functioning during deglaciation as proglacial channels, one would expect them to become infilled with sediment.

Dunmore Cave

The geographical proximity of Dunmore Cave would suggest that this geomorphic feature should be looked at in tandem with the Ballyfoyle channels. The allogenic nature of the majority of the clasts within the gravel sequences of the Rabbit Burrow and 'The 44' points to the deposits being laid down from a stream which originated outside of the limestone cave. The shale bedrock outcrops 500 m to the north of the cave. If the sediments had been transported as sediment load within a modern stream system (which would have passed over the Upper Carboniferous sandstones and shales and subsequently disappeared through a sink into the karstic system) the clasts, particularly those clasts that are not shale in lithology and therefore are more likely to round, should be more rounded. Because of the angular nature of the clasts, it is suggested that they were transported within a glacier and found their way into the cave beneath this glacier. Meltwater released at the base of the glacier would contain the same clasts of the same characteristics as those carried within the glacier. This meltwater may subsequently have found its way into the karstic system via a sink.

The dearth of comparable glaciofluvial gravels on the surface (Figure 2) also points to the sediments within the cave being of subglacial origin. If the sediments were of proglacial origin, similar deposits should be found on the surface. The nearest surficial glaciofluvial deposits are those within the Dinin valley, 1 km to the west of the cave. Two samples were taken from a borehole which penetrated 12.5 m of gravels within the townland of Inchabride (NGR 250260 165560). This extensive gravel body (Figure 2), which occupies the valley of the modern Dinin River, is interpreted as proglacial (Hegarty 2003). Bedrock was not hit within the hole, therefore indicating that this body of gravel is considerable both in depth as well as in extent. These proglacial gravels are composed mostly of Upper Carboniferous clasts (58%) but contain 15% limestone clasts and 22% chert – the Middle and Lower Carboniferous fraction is therefore close to 37% of the total stone count from the sample taken ($n = 336$; bulk sample taken from 3.5 m depth). One Galway granite clast was also recovered from the gravels at this location. The difference in lithology between these proglacial deposits and those found within the cave system points to difference in genesis for the two sequences, with one being proglacial and the other subglacial in origin.

Dunmore Cave is developed within the Clogrennan Formation, which lies unconformably beneath the Carboniferous shales. The sediments which infill the Rabbit Burrow area within the cave must have been intruded through an entrance to the north, perhaps a sinkhole, as some of the clasts are large pebble sized (8% of clasts are above 0.02 m a-axis) and are incapable of finding their way into the system via permeable flow through the bedrock. This sinkhole has not been identified, and no sign of it is seen on the surface to the north of the cave. This again points to the sediment having been deposited from subglacial meltwater, as a glacier passing above the cave at the time of deposition may also have deposited till on the surface and this would blanket the entrance to any subterranean sink. Nonetheless, the presence of glaciofluvial deposits within the cave system points to the fact that subterranean conduits were possibly in use beneath the ice sheet in the study area. Further investigation to identify the input point of these sediments, perhaps using geophysical techniques, would be worth pursuing. Simms (2000) identified another input source for glacial sediments within caves – the washing out of a till plug. In the case of Dunmore Cave, the amount of sediment (approximately 450 m^3 of sediment within the Rabbit Burrow alone, based on the survey diagram by Drew and Huddart 1980) would suggest that this is not the genesis of this sediment fill.

What makes this particular area around the cave even more intriguing is the proximity of Dunmore Cave to the deep meltwater channels which have been interpreted as Nye channels. The termination of the meltwater channels coincides with the boundary between the shale bedrock and the karstic limestone formations to the south (Figure 1b). This is significant for the study as it strengthens the hypothesis that the characteristics of the underlying bedrock aquifers determined the subglacial hydrology and, in particular, the type of conduit system to develop at the ice–substrate interface.

The formation of the Nye channels described above has been attributed to high subglacial hydrostatic pressures. The termination of these channels along the geological boundary suggests that, at this point, the high hydrostatic pressure dissipated. One explanation for the dissipation of high subglacial water pressures at this point is that another conduit system was initiated. There is no evidence (such as the presence of tunnel-fill eskers) to suggest the formation of R-channels (as described by Röthlisberger 1972). One other type of subglacial conduit system that seems probable within this area of karstic bedrock is groundwater flow. Evidence for this has been found within Dunmore Cave, as described above. However, to date no evidence for this has been found to the south of the channels.

Boulton et al. (1995) suggest that the aquifers that underlay the core of the European ice sheets had sufficient transmissivity to discharge all subglacial meltwater and therefore to bring water pressures below ice-overburden pressures. However, groundwater flow is often not capable of draining all the water from the base of an ice sheet (Hindmarsh 1998). Piotrowski (1997a) suggests that Boulton et al. (1995) based their calculations on 2D groundwater flow only, and Piotrowski, like Hindmarsh, disagrees with the argument by Boulton and colleagues. The complexity of the glacial substrate is particularly true in the case of Ireland, where the complex geological history has produced an equally complex series of aquifers and aquitards, often not extending for great distances. Therefore, under the Irish Ice Sheet, a further method of meltwater drainage such as those mentioned above may also have operated. This situation of small-scale changes of aquifer characteristics appears to be true of the study area, and this paper has looked at the effects of this on the landscape.

Conclusions

The channels mapped in the area around Ballyfoyle are confirmed here to be Nye channels, created beneath the ice sheet during glaciation. This interpretation is based on their geomorphology (dry channels, undultating long profiles, trapezoid shape). When the location of these channels was overlain on the bedrock geology maps it was seen that they occurred only within areas of poor aquifers, although some of the channels may owe their incision to the reorganisation of equipotential lines when the ice sheet came up against topographic barriers, such as have also been described in Washington State by Booth and Hallet (1993), and in Enniskerry, Co. Wicklow by McCabe and Ó Cofaigh (1994). The subglacial substrate therefore is thought to have influenced the subglacial hydrology of this area, giving rise to these Nye channels incised into the bedrock in areas of poor water transmissivity.

A further subglacial meltwater route was discussed in the light of this finding. While for many years (Coleman 1965, Drew and Huddart 1980) it had been known that a passage of Dunmore Cave was infilled with sediment that was interpreted to be glaciofluvial in origin, this sediment had previously been interpreted as proglacial (Drew and Huddart 1980). However, when these sediments were examined it was seen that they were more akin to subglacial glaciofluvial sediments due to their angularity and the fact that they were allogenic. The idea of subterranean drainage beneath ice sheets is not new. It has already been described by Ford (Smart and Ford 1983, Ford 1996) as occurring beneath the Castleguard Cave system beneath the Colombia Icefield. Sharp et al. (1989) have also reported karstic drainage beneath the Glacier de Tsanflueron in Switzerland. However, widespread subterranean drainage has not been widely documented within ice sheets. Ireland is an ideal candidate for this type of widespread subterranean drainage.

Acknowledgements

I would like to thank the OPW and those working in the Visitor Centre for access to Dunmore Cave and their hospitality, the Royal Irish Academy for permission to redraw part of Figure 6 and the Geological Survey of Ireland for permission to reproduce Figure 3. I am also very grateful to Michael Sheehy for assistance in the field and to R. Meehan for helpful suggestions on a previous draft of this paper. Anonymous reviewers made many very helpful suggestions which improved the paper greatly.

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